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# Hearing Aids and Digital Wireless Telephones

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## ABSTRACT

A highly audible interfering sound may be created in hearing aid outputs by the pulsatile electromagnetic signals generated by some digital cellular telephones (DCT). At its worst, this undesirable signal totally dominates the audio processing of the hearing aid and makes it unusable. The degree of interference generated is a function of the type of DCT technology, the type or style of hearing aid, and how many precautionary measures have been taken in the hearing aid design to reduce interference. Engineers from telephone companies and hearing aid engineers have worked together with the encouragement of hearing aid consumers and the Federal Communications Commission to reduce this interference problem. As a result, considerable strides have been made, particularly by hearing aid companies, toward improving the immunity of hearing aids to DCT interference. Many of these same engineers have participated in national and international standards committees to develop viable methods for assessing the amount of immunity to DCT interference provided by hearing aids and the emission levels from DCTs. The process of harmonizing these standard assessment techniques is ongoing.


**KEYWORDS:** Interference, immunity, emission, digital, cellular, telephone

**Learning Outcomes:** Upon reading this article the reader should (1) have an overall technical understanding of the cause and effect of digital cellular telephone interference in hearing aids and how it can be measured, and (2) know generally some of the methods that have been used to alleviate the interference produced by digital cellular telephones in hearing aids.

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The Hearing Aid Compatibility Act of 1988 mandates that wire-line telephones manufactured for sale in the United States be hearing aid compatible. To date, no such requirement exists for wireless telephones, although consumer groups have recently petitioned the Federal Communications Commission (FCC) to apply the same rule to cellular telephones.[1] One problem standing in the way of achieving compatibility for digital wireless telephones is the interference they cause in hearing aids.

When a wireless telephone is used close to a hearing aid, there is a radio frequency (RF) near-field illumination of the hearing aid. Depending on the particular technology being considered, in many but not all cases, the RF signal used by digital cellular telephones is turned on and off periodically, or temporally modulated. (Analog cellular telephones do not use temporal modulation of the RF signal and thus do not generally introduce interference in hearing aids.) Electromagnetic interference produced by a digital cellular telephone (DCT) is caused mainly by this temporally-modulated RF signal being picked up by the wiring in the hearing aid.[2] Much like the workings of an amplitude-modulated (AM) radio, the pulsing high-frequency RF signal produced by the DCT is demodulated by diode rectification in the hearing aid amplifier stages, thereby extracting the modulated envelope shape, which is a low-frequency audio signal that sounds typically like a buzz. At its worse, the buzz dominates and renders hearing aids unusable by blocking their processing of desired signals, and, in some cases, is so intense that it can exceed the threshold of pain for listeners with hearing loss.

This interference often leaves hearing aid wearers unable to use DCTs in the normal way, held close to their ears. A partial solution, such as that employed in hands-free cell telephone operation, may not be acceptable as the only solution for many hearing aid wearers. Achieving total compatibility with DCTs for many hearing aid wearers includes a visually normal appearance when using these devices with their hearing aids.

Initially, some members of the telephone manufacturing industry were not very sympathetic. The chairman of the Global System Mobile (GSM) MoU, the oversight group for GSM vendors, wrote to Reed Hundt, FCC chairman, "some of the research suggests that a small percentage of all hearing-impaired persons use old, inferior-quality hearing aids, and therefore may be unable to use high-power wireless telephones."[3] Hearing aids are not the only device in which digital cellular telephone interference (DCTI) causes problems. Cellular phones also have caused such severe interference for pacemakers and electric wheelchairs that they were at one time banned from use in hospitals in Sweden.[3] Physicians at the Mayo Clinic in Rochester, MN, recommended that persons with cardiac pacemakers not carry digital cellular telephones with power switched on in their breast pockets. In the Mayo experiments, measurable interference with pacemaker electronics was noticed 12.9% of the time when the phone's antenna was placed over the pacemaker. Symptoms of interference, including rapid heartbeats, lightheadedness, and dizziness were noticed in 7.2% of the tests.[4] A prominent pacemaker manufacturer recommended that patients with implanted pacemakers or defibrillators maintain a minimum separation of 1 foot between a high power digital cellular phone (3 W < transmit power < 20 W) and the implant site whenever the phone is on.[5] A few proactive communities in the United States recognized this problem early on and took official action. For example, city council members in San Diego and San Jose, CA, stopped temporarily the construction of new wireless digital phone systems for their regions because they interfered potentially with the operation of pacemakers, hearing aids, electric wheelchairs, and automobile air bags.[6]

## THE NATURE OF THE INTERFERENCE: BYSTANDER AND WEARER, EFFECTS OF PHONE TECHNOLOGY, AND TYPE OF HEARING AID

Two types of electromagnetic fields emanate from a DCT, an electric or "E" field (produced as a far field) and a magnetic or "H" field (produced as a near field).[2] Each of these fields produces different types of interference characteristics in hearing aids. Because the E field emission is considered to be far field, it is associated mainly with bystander interference, that which would occur for a hearing aid wearer in close proximity to another person using the DCT. The H field is associated more with interference produced by the hearing aid wearer attempting to use a DCT; this is known as *wearer interference*. Consideration of how the near-field electromagnetic field characteristics interact with a hearing aid is extremely important when assessing what immunity a hearing aid would provide to DCTI when the hearing aid wearer is using the phone. DCTI is generally worse when hearing aids are operating in induction pickup mode, as compared with microphone pickup mode, because there is little difference in the base-band desired magnetic signal from the telephone and the interference signal. Consequently, the reduction of magnetic interference from cellular telephones for hearing aids in induction pickup mode is particularly problematic because the interference has a similar nature to the desired magnetic signal from telephones and room and neck loops. Many hearing aid wearers have not been able to use their instruments in telecoil setting to connect with their DCTs because of the strong DCTI signals. It is more difficult to reduce DCTI in behind-the-ear hearing aids (BTE) than in custom hearing aids, because of their larger sizes and hence longer wire lengths than in smaller custom models.

## INPUT-REFERRED INTERFERENCE LEVEL

The input-referred interference level (IRIL) is a quantification in dB sound pressure level (SPL) of the equivalent input signal level that would be produced by a DCT interference signal. IRIL is thus related to the signal-to-noise ratio (SNR) produced by DCTI in the hearing aid input signal. Studies by Killion et al[7] and Levitt et al[8] show that at least a 20-dB SNR is required with a 50-Hz buzz interference signal, and at least a 25-dB SNR is required with a 217-Hz buzz interference signal, for the telephone signal to be acceptable to hearing aid wearers, regardless of degree of hearing loss (Fig. 1). Because a telephone produces about an 80-dB SPL acoustic signal at the hearing aid microphone inlet, the IRIL can be calculated roughly as 80 − 25 dB SNR = 55 dB IRIL. This figure agrees with the level at which interference becomes unacceptable in the NAL[9] study (about 20 dB above a typical A-weighted hearing aid equivalent input noise level).

One issue in simulating the DCT interference signal is what field strengths in volts/meter (V/m) are most appropriate to use. The field strength at 1 m from a 2-W GSM mobile telephone radiating at full power ranges from 3 to 10 V/m.[9] Higher field strengths may be radiated with other types of telecommunications technology. One hundred volts/meter or higher is a realistic field strength that a hearing aid is exposed to when placed near a DCT receiver.[9]

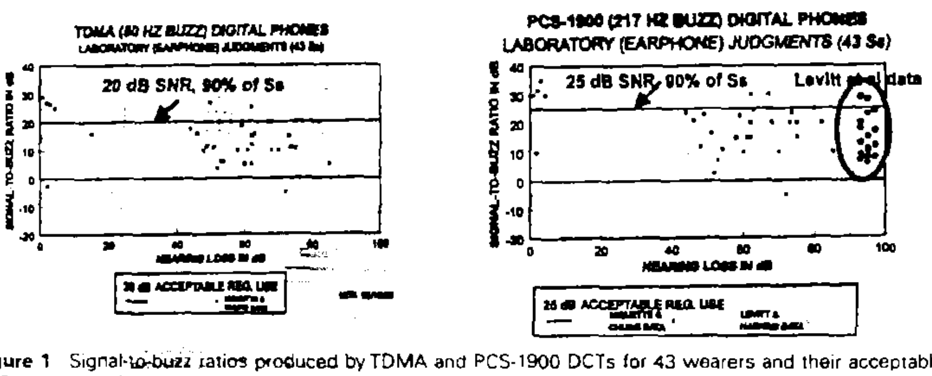


Figure 1 Signal-to-buzz ratios produced by TDMA and PCS-1900 DCTs for 43 wearers and their acceptable SNR. Reprinted from Killion (2000)[24] by permission.

The intensity of DCTI normally decreases in inverse proportion to the square of the distance between the DCT and the hearing aid.[8] Tests completed by Per Vittendorf from the EMC Lab in Denmark indicated that a simulated GSM transmitter could cause interference up to 30 m away. In reviewing studies of DCTI in hearing aids, one finds that the effects of simulated interference signals of 1, 3, and 10 V/m field strength have been evaluated the most. However, it is obvious that immunity to a 3 V/m simulated RF modulated signal (as in the original International Electrotechnical Commission [IEC] 60118-13 standard) is not adequate to reflect real-world immunity, even for bystander interference, for DCTs in Europe that actually produce up to 160 V/m.[7] Macfarlane[10] has shown that peak E field strengths derived with a dipole for a GSM mobile phone can approach over 200 V/m rms at a 1-cm distance from the phone.

The amount of interference produced by a DCT in a hearing aid was expressed in most of the early studies essentially as what equivalent input SPL signal would cause that level of signal in the hearing aid output. For example, in the Australian study of interference produced by 900-MHz GSM phones,[9] interference levels were expressed by what level of electromagnetic field strength in dB re: 1 V/m would produce an equivalent of a 40-dB SPL 1-kHz input signal in a hearing aid. Immunity levels were assessed both before and after treatment to the hearing aids (Fig. 2). The amount of improvement was the increase in carrier field strength required to produce an interference signal in the hearing aid equivalent to that of a 40-dB SPL 1-kHz input signal. One outstanding issue is whether the IRIL for user interference should be computed for any relative orientation of the telephone and hearing aid or for the normal orientation. A consideration in this trade-off is whether the normal orientation is worst case or not. Mandating IRIL for worst-case orientation ignores the potential advantage of a favorable orientation to minimize interference.[11]

The National Acoustic Laboratory (NAL) report[9] stated that for acceptable immunity to interference, a hearing aid would have to produce less than 40-dB SPL equivalent input signal for both a wearer interference signal greater than 30 V/m and for a 9- to 30-V/m bystander interference signal. The abbreviation for this immunity level is ILM40, and the units are in volts per meter. Required immunity level estimates were divided into two levels of interference: (1) tolerable or moderately perceptible and (2) virtually no interference. The type of interference also was categorized for bystander interference (class 1) and wearer interference (class 2). A summary of the required immunity levels for tolerable interference and no interference for bystander and wearer conditions using the simulated test signal is reproduced in Table 1. The NAL report[9] also stated that the measured improvements in immunity levels in hearing aids for which wires were shortened, as well as electrostatic shielding, metal-filled case parts and shunt capacitors added across the

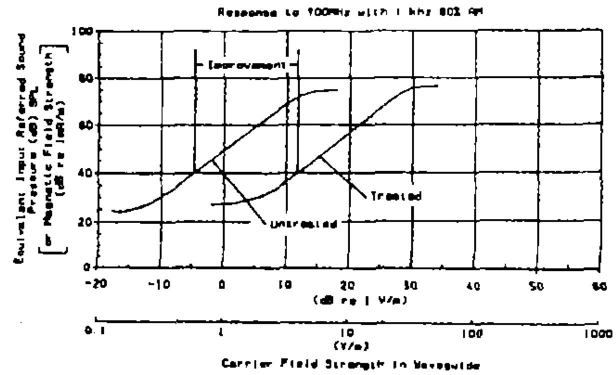


**Figure 2** Hearing aid equivalent input interference SPLs as a function of simulated RF-modulated carrier field strength before and after treatment. Reprinted from NAL (1995)[9] by permission.

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**Table 1 Proposed Minimum Test Limits for Field Strength of Simulated DWT Output Signal for Tolerable Interference Level (11 dB re: 1 V/m) and No Interference (24 dB re: 1 V/m) in Normal-Hearing Listeners and the Estimated Equivalent Input Signal SPL of the Interference Signals Produced in Hearing Aids for Bystander (Class 1) and Wearer (Class 2) Conditions**

| Service | Severity Field Strength of Carrier (80% 1 kHz Amplitude Modulated 900 MHz Carrier Wave) (V/m) | Test Level Equivalent Input Referred Sound Pressure (dB SPL) | |
|---|---|---|---|
| | **Interference Criteria** | **Tolerable Interference** | **No Interference** |
| | for required ILM40 equal to (dB re 1 V/m) | 11 | 24 |
| Class 1 | 3 | 37 | 17 |
| | 10 | 58 | 32 |
| | 30 | 77 | 51 |
| | for required ILM40 equal to (dB re 1 V/m) | 28 | 36 |
| Class 2 | 10 | 24 | 8 |
| | 30 | 43 | 27 |
| | 100 | 64 | 48 |

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amplifier input, ranged from −4 dB to +34 dB. Shortening the wires between microphone and amplifier input provided the most benefit.

## DIFFERENCES IN INTERFERENCE ACROSS DCT TECHNOLOGIES

The frequency at which the carrier is switched on and off and the modulation depth in part determine the interference level. The RF signal emanating from a DCT periodically pulses in amplitude with a large modulation depth in some DCT types.

Time Division Multiple Access (TDMA), introduced in 1992, was originally used in satellite communications to increase transmission channel capacity. TDMA is used as an air interface technique in GSM networks in Europe. The TDMA channels are given a periodic time slot within a frame, thus effectively negating interference between channels. In TDMA, time slot synchronization is critical for effective transmission. It has a 50-Hz repetition rate (20-ms period) and a modulation interference signal with a 33% duty cycle (at 3 users/carrier), so the burst time is 6.67 ms (Fig. 3). The output noise spectrum from a completely in-the-canal hearing aid (CIC) in an HA-1 2-cm$^3$ coupler produced by a DCT with TDMA technology is shown in Figure 4.

The European version of the GSM was first deployed in Germany in 1992. For GSM technology, the temporal envelope of the interference signal modulates or pulses at a 217-Hz repetition rate (4.6-ms period). Because there is a 12.5% duty cycle (8 users/carrier), the du-

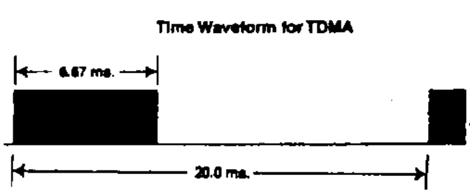


**Figure 3** Carrier burst duration and periodicity of a TDMA DCT output signal.

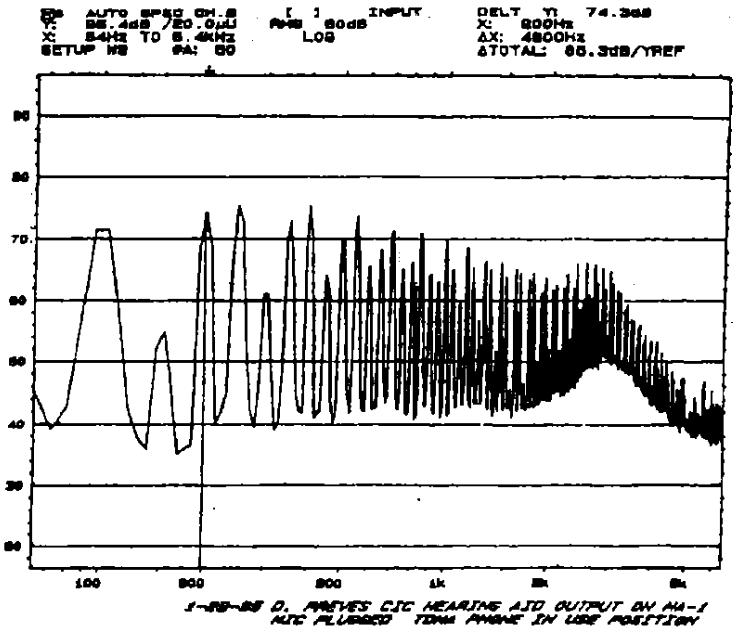

Figure 4 Spectrum of CIC hearing aid output in HA-1 2 $cm^3$ coupler produced by a TDMA DCT. Microphone inlet to hearing aid was covered.

ration of each burst or pulse for GSM is 1/8 period or 0.577 ms for GSM systems (Fig. 5). Some researchers have shown a 15-dB greater interference with GSM DCTs than with TDMA phones. In the United States the GSM system is known as Personal Communication Systems (PCS) 1900.

Code Division Multiple Access (CDMA) is a more recently introduced technology, originally developed by the military to help solve conflicts in transmission communications. CDMA is said to have higher data rates and more secure transmission than either GSM or TDMA and may use channel frequency hopping. CDMA uses a spread spectrum signal to distinguish between channels, which is more like frequency-modulated signals, whereas GSM and TDMA have gated temporal modulation that are more like AM signals. CDMA does not temporally modulate the RF signal significantly, making much better use of the available RF transmission bandwidth. The little there is occurs at 2 Hz (about 30 users/carrier). Some researchers have shown a 10-dB greater interference with TDMA than with CDMA. Early reports even indicated much less or no interference produced by DCTs with CDMA technology.[7,12] Figure 6 shows data developed by the developer of CDMA technology, Qualcomm,[12] comparing the average distance from the phone to the hearing aid for audible interference for five persons with GSM and CDMA DCTs. Six different hearing aids from three manufacturers were tested, including BTE, in-the-ear hearing aid (ITE), and in-the-canal hearing aid (ITC). The same power amplifier and radiating antenna were used for both signal types. The GSM signal (European TDMA) was actually simulated by amplitude modulating an RF signal generator, whereas the 800-MHz CDMA signal was

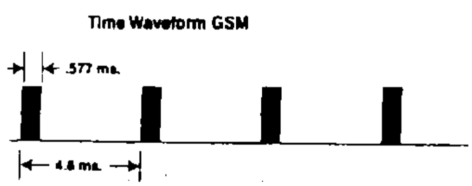


Figure 5 Carrier burst duration and periodicity of a GSM DCT output signal.

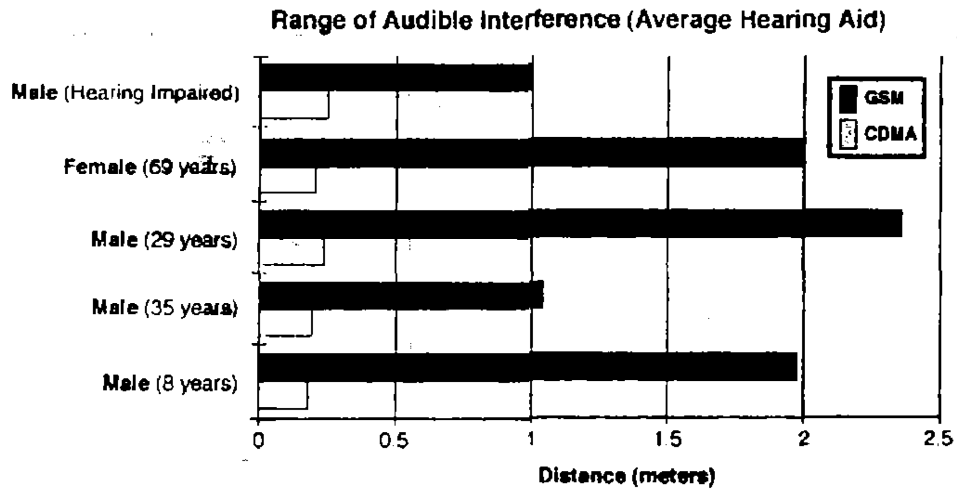


**Figure 6** Comparison for five listeners of distance from DCT to hearing aid for audible interference with GSM and CDMA DCTs. Reprinted from Lambert and Frazier (1994)[12] by permission.

derived from a Qualcomm CD-7000 portable phone at maximum transmit power. The vocoder rates were not specified. The authors concluded that the CDMA signal could not be detected unless the distance was within 0. 5 m, whereas the GSM signal could be detected at distances of 1 to over 2 m from the hearing aid under test. It is important to recognize that the interference characteristics and immunity of hearing aids for a 2-W 900-MHz carrier (such as GSM), which has been widely studied, may be altogether different from that at higher frequencies, such as 1900 MHz or even greater, which more recent DCTs use.

## DIFFERENCES ACROSS HEARING AID MODELS IN THE AMOUNT OF INTERFERENCE CAUSED BY DCTS

Early reports stated that many BTEs had severe interference problems[9] but many CICs had no interference problems for TDMA and GSM field strengths of up to 100 to 200 V/m.[13] This latter result was in contradiction to a University of Oklahoma report that showed little or no difference in interference levels between some hearing aid model types and that ITCs had less interference than CICs.[14] The reader is referred to Figure 7, which shows the average annoyance ratings at 25-cm distance for PCS-1900, TDMA-800, and CDMA DCTs by hearing aid type.[14]

## THE EUROPEAN HEARING INSTRUMENT MANUFACTURERS ASSOCIATION STUDY

Realizing the significance of the problem, the European Hearing Instrument Manufacturers Association (EHIMA) contracted with Delta Acoustics Laboratory and TELECOM in Denmark to perform a study on the interference produced by GSM wireless telephones in hearing aids.[15] A peak field strength of 10 V/m was used for a simulated signal, because in the authors' opinions that RF field corresponded to a maximum power output from an 8-W mobile telephone at a 2-m distance (or 2 W at 1 m). The EHIMA study[15] concentrated only on measures to simulate bystander interference. The test setup used for the EHIMA study[15] is shown in Figure 8. A tubing length of 500 mm between the coupler and the hearing aid was used to ensure that the metal in the coupler did not interfere with the electromagnetic field at the hearing aid. The report noted that the telephones produced interference in all hearing aids tested and that simulated fields of only 1 to 3 V/m

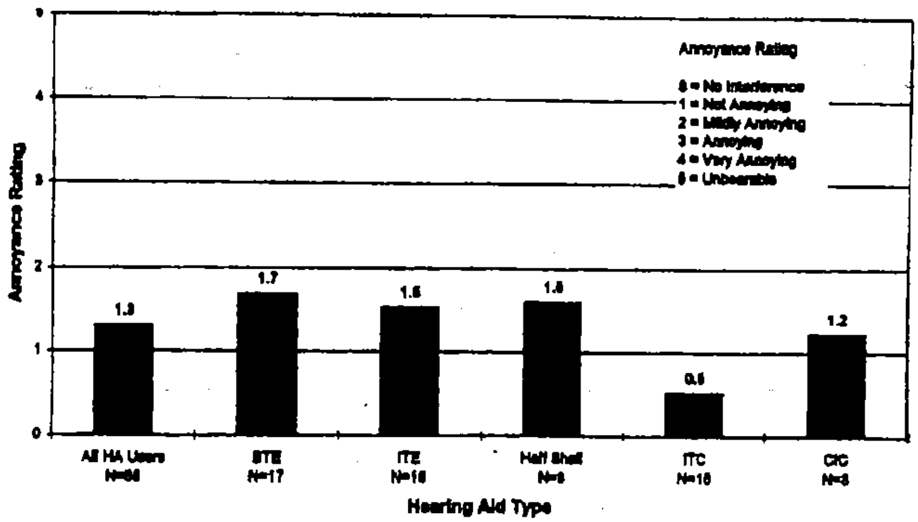


**Figure 7** Average annoyance rating at 25 cm distance by hearing aid type. Reprinted from University of Oklahoma (1996)[14] by permission.

and 5 to 32 V/m, respectively, were needed to produce noticeable interference in BTEs and ITEs. The study reported that a 40-dB SPL input-related noise level would be slightly annoying to five normal hearing persons and an *overall input-related interference level* (OIRIL) of 55 dB SPL would probably produce acceptable performance. Only the low-frequency portion of the interference signal was important in calculating the OIRIL. It was found that the human head significantly attenuates the GSM signal when it is between the interference source and the hearing aid. The EHIMA report[15] would later serve as the basis for the IEC 60118–13 interference measurement standard; in fact, an early draft of the IEC standard was part of the EHIMA report.[15] The concept of IRIL also is used in the American National

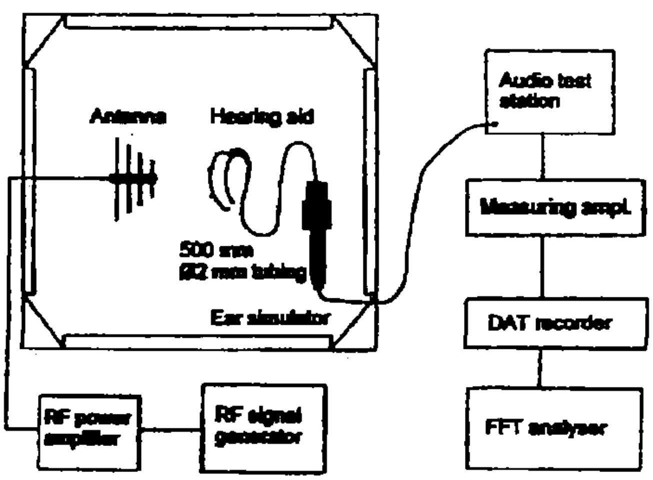


**Figure 8** Test setup for study of interference produced by DCTs in hearing aids worn on bystanders. Reprinted from EHIMA (1995)[15] by permission.

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Standards Institute (ANSI) C63.19 standard for measuring interference produced in hearing aids by DCTs.

## NAL INVESTIGATIONS

In work leading up to the NAL study,[9] Joyner et al[16] reported that the peak power levels produced by GSM phones operating at 900 MHz ranged from 2 W for a handheld phone to 8 W for a transportable unit. Joyner and colleagues found that the hearing aid output buzz caused by a DCTI became noticeable at a level about 10 dB higher than the ambient noise of the hearing aid. Table 2 shows the RF field strength and hearing aid output SPL and its relation to the output noise floor for five BTEs and four ITEs for just noticeable interference. It is interesting to note that the interference threshold for telecoil mode is similar to that for microphone mode for most of the BTEs and that the interference threshold for the ITEs requires a higher RF field than for the BTEs. In this study, the RF field was simulated by an RF generator and power amplifier. The 2-W unit produced field strengths of up to about 40 V/m at 0.1-m distance and about 6 V/m at 1-m distance. However the 8-W transportable phone actually produced about 80 V/m at 0.1-m distance and 12 V/m at 1-m distance.

The NAL, in conjunction with the Telecom Research Laboratories of Australia, the Deafness Forum of Australia, the Spectrum Management Agency, and hearing aid suppliers, initiated a comprehensive study of interference caused in hearing aids by GSM DCTs and published the results in a report.[9] A variety of BTEs and ITEs mounted remotely (so as to be far from a metal object) via a 500-mm long tubing that was attached to a 2-cm³ coupler were evaluated for immunity to interference using a specially designed waveguide that simulated the interference signal up to a field strength of 100 V/m. The interference signal was simulated by a 900-MHz carrier 80% modulated by a 1000-Hz sinusoid. The equivalent input referred sound pressure of the interference signal was calculated. These measurement procedures were adopted in the initial version of IEC standard 60118–13 for measuring interference levels produced in hearing aids by cellular telephones.

In the study,[9] subjects also were asked to rate how annoying the interference was at distances of 1 m and 0.7 m from DCT to hearing aid. Results indicated that those with hearing loss wearing the type of ITE evaluated were unlikely to experience bystander interference *from*

**Table 2 The Electromagnetic Field Strength and the Corresponding Hearing Aid Output SPL for a Noticeable Difference of Interference in Five BTEs and Three ITEs**

| | Microphone Switched In | | | Telecoil Switched In | | |
|---|---|---|---|---|---|---|
| Hearing Aid | RF Field (Volts/m) | Hearing Aid Output (dB SPL) | dB Above Noise (no RF) | Threshold (Volts/m) | Hearing Aid Output (dB SPL) | dB Above Noise (no RF) |
| **Behind-the-ear hearing aids** | | | | | | |
| PPSCL | 3.1 | 85.5 | 9.5 | 3.1 | 67.0 | 5.0 |
| PPSC | 2.8 | 94.5 | 9.5 | 4.9 | 87.0 | 10.0 |
| VHK | 0.7 | 89.5 | 9.5 | 0.4 | 77.0 | 12.0 |
| VLA | 1.6 | 62.0 | 12.0 | 2.0 | 59.0 | 12.0 |
| PPCL4 | 3.1 | 85.0 | 11.0 | 3.1 | 74.5 | 9.5 |
| **In-the-ear hearing aids** | | | | | | |
| JLFR Sonata | 9.4 | 69.5 | 10.0 | | | |
| S Serenade | 4.9 | 66.0 | 10.5 | | | |
| IT312 NAL-Phox | 32.3 | 78.0 | 9.5 | | | |

Reprinted from Joyner et al, (1993) by permission.[16]

others using DCTs and that the treatments mentioned previously (see pages 46–47) reduced significantly the interference levels in the BTEs evaluated. However, none of the hearing aids evaluated, even though treated, could provide their wearers access to using handheld DCTs in the normal way. One result of the NAL 1995 study, that a 42-dB SPL input related noise would be noticeable, correlated somewhat with the EHIMA study[15] in which a 40-dB SPL input-related noise level was found to be slightly annoying to five normal-hearing persons.

## OTHER EARLY STUDIES OF INTERFERENCE

Hansen and Poulsen[17] simulated the modulations produced by DCTs with periodic square wave signals, mixed these with environmental noise or speech, and presented the result through a digitally simulated master hearing aid with an Etymotic Research ER-4B insert earphone to 17 persons with hearing loss. Results showed that GSM simulated noise was noticeable but not annoying at an input-referred level of 45- to 48-dB SPL, which is comparable to the NAL 1995 result of 42-dB SPL input-referred for an annoying response level.

Some studies have used a 460-mm long, 2-mm diameter Tygon tubing to couple hearing aids to a 2-cm$^3$ coupler to ensure that the metal in the coupler does not interfere with the electromagnetic fields produced near the hearing aid. Such a practice considerably changes the output spectrum from hearing aids in an artificial manner and can affect the measurement results.

## JOINT EFFORT TO REDUCE INTERFERENCE

Hearing aid engineers and telephone company engineers began meeting in 1996 in response to a mandate by the FCC to fix the DCTI problem in hearing aids. The first formal meetings were held in Washington, DC, at a Wireless Summit conference, initiated by the FCC, which involved members of hearing-impaired consumer groups interacting with representatives from the hearing aid manufacturing and telephone manufacturing industries. The primary goal of the conference was to improve the level of understanding between the three groups concerning DCT/hearing aid compatibility and the need for persons with hearing loss to have accessibility to digital wireless telecommunications. The conference began with an all-day plenary session that presented profiles on the wireless industry, including regulatory aspects and the physical nature of wireless technologies and their interaction through electromagnetic coupling with hearing aids; the nature of hearing loss and available technologies that either aid or prevent effective communications; the state of hearing aid technology and assistive listening devices and potential solutions to DCTI.[18]

Three working groups were set up, comprising representatives of each of the three main interest groups and outside experts. The working groups were charged with reviewing available data, assessing the level of technical understanding of interference and compatibility, and exploring the feasibility of providing short-term and long-term solutions, including time lines with which to accomplish their assigned tasks. Each working group had three co-chairs selected by a Steering Committee prior to the Summit Meeting:

1. Short-term user and bystander interference group. Assignment: Identify interim solutions to both hearing aid wearer and bystander interference; review overall research activities. Co-chairs: Harry Levitt, The Lexington Center; Michael Sacha, Starkey Laboratories; Charles Spann, Northern Telecom.
2. Long-term user and bystander interference group. Assignment: Identify potential long-term solutions to both hearing aid wearer and bystander interference for cost and technical feasibility; review research activities. Co-chairs: Horst Arndt, Unitron Industries; John Darby, Consultant; Barry Kratz, Ericsson, Inc.
3. Compatibility group. Assignment: Identify possible factors that would help to achieve electromagnetic compatibility between hear-

ing aids and digital wireless telephones; develop a proposed definition of compatibility. Co-chairs: Ray Millington, Motorola, Inc.; David Preves, Argosy Electronics; Jim Tobias, Inclusive Technologies.

These meetings served as a catalyst to get the different groups talking to each other. Subsequently, groups of hearing aid and telephone company engineers continued the dialog, initiated in 1996 during the Wireless Summit meetings, at the University of Oklahoma Center for the Study of Wireless Electromagnetic Compatibility (EMC).

Early on a group comprised of telephone company representatives, University of Oklahoma staff, three engineers representing the hearing aid industry, and one audiologist assisted in designing a multiphase study to determine the level of interaction between wireless devices and hearing aids.[19] The plan called for identifying immediate cost-effective solutions to the interference problem by modifying present hearing aids and telephones and suggesting future designs. The EMC Center conducted their study on DCTI in hearing aids using both instrument-based electromagnetic interference (EMI) testing and a subject-based protocol comprised of persons having normal hearing and persons with hearing loss. The study followed much of the testing protocol of the EHIMA[15] and NAL[9] studies, with the exception that actual PCS phones were used, having GSM technology operating at 1900 MHz and TDMA and CDMA technology operating at 800 MHz, instead of RF generator signals simulating the 900-MHz GSM 2-Watt handheld and 8-Watt mobile phones. Human subject testing was designed to determine the extent of the interaction of hearing aids with a variety of digital wireless communication technologies.

Research activities at the center have been funded principally by telephone companies, and results have been documented frequently and publicly. In their Phase I progress report dated April 29, 1996, that evaluated worst-case bystander interference,[14] the degree of interference was shown to vary with hearing aid type, hearing loss configuration and severity, and the type of wireless telephone technology. In over 80% of the tests, hearing aid wearers did not experience any significant interference unless a DCT was within 1 m. Even when interference was perceived, it became annoying for only 2% of the subjects at 1-m distance and for 12% of the subjects at 0.5 m. In Levitt et al,[8] the consequences of bystander interference from PCS 1900 and TDMA DCTs for 53 test subjects are somewhat more serious: 25 to 38% of BTE and ITE wearers could detect DCTI at distances greater than 2 feet from their hearing aids, and 8 to 14% reported an annoying interference level at more than 2 feet away.

Of the phone technologies tested at the University of Oklahoma EMC Center, CDMA at 800 MHz resulted in the lowest interference levels across all measures. Of the hearing aid types tested, BTE models had the most interference and ITCs had the least interference. In Phase II of the study, the mechanisms of interaction were identified, and the effectiveness of various short-term and long-term solutions was tested on human subjects to determine how much the interference had been reduced. Emphasis was placed on correlating acoustic measures of interference levels to subjective assessments of interference levels. For this phase, hearing aids and telephones were provided by many of the participating companies to determine how much the interference had been reduced in modifications and new designs.

## ANSI C63.19 STANDARD

The idea for forming a joint working group to formulate an ANSI standard with which to define and measure DCT/HA compatibility was first advocated by Stephen Berger, then at Siemens Telecommunications, at a meeting at the University of Oklahoma Electromagnetic Compatibility Center. Ultimately, he and Thomas Victorian, Starkey Laboratories, became co-chairs of the ANSI working group. Over the next several years, many engineers from both the hearing aid and telephone industries spent countless days communicating, making measurements, drafting the ANSI standard, and attending the many working group meetings over the 4 years it took to prepare the

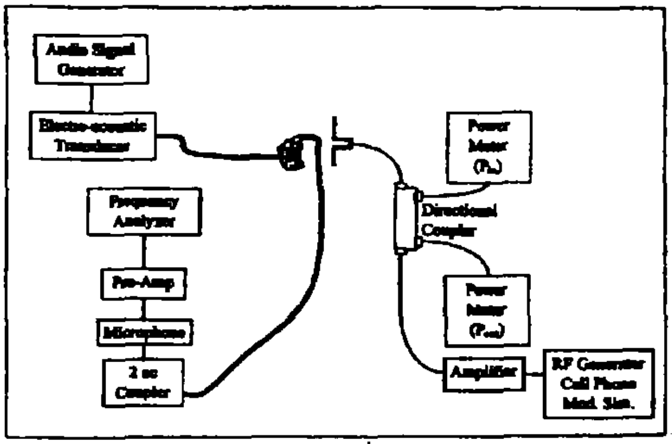


**Figure 9** Test setup from the ANSI C63.19 standard showing the dipole antenna for simulating the near-field electromagnetic field generated by DCTs. Reprinted from ANSI (2001)[20] with permission.

standard. The standard recommends that wireless communication devices be measured for near RF electric field emissions, near RF magnetic field emissions, and audio-band magnetic signal strength and frequency response of the inductive signal provided for hearing aids operating in telecoil (induction pickup) mode. The standard recommends that hearing aids be measured for their near-field RF immunity in both microphone and induction coil operating modes. A dipole antenna is used to simulate the near-field radiation from DCTs. These measurements are made in the near field to simulate the more intense electromagnetic field a hearing aid would be exposed to when the wearer is using a DCT. Figure 9 is a diagram reproduced from the C63.19 standard of the near-field test setup showing the dipole antenna.

The ANSI C63.19 standard contains detailed test setup and test protocol information with which to categorize DCTs into classes of radiated electromagnetic energy levels and hearing aids into classes of immunity levels. The standard also recommends what constitutes an acceptable degree of matching between telephone emission classes and hearing aid immunity classes.[2] Table 3 is reproduced from the C63.19 standard showing the E and H field immunity levels for hearing aids for < 55 dB IRIL and E and H field emission levels for cell phones. The C63.19 standard notes that because the interference output of typical hearing aid circuitry is proportional to the square of the RF field, a 5-dB change in RF field strength produces a 10-dB change in the interference level.

Ignoring the absolute immunity and emission levels, classifications of the immunity levels of hearing aids and electromagnetic emissions from DCTs are given in Table 4, as adapted from Victorian.[2] To use the table, a combination of the cell phone rating with the hearing aid rating totaling three or better should allow normal hearing aid use. As a useful reference point, most cell phones have an E field emission level of less than 41 V/m, which puts them in the U2 category.[21]

## IEC 60118-13 STANDARD[22]

One outgrowth of the EHIMA study[15] was an IEC DCT/HA compatibility standard. Initially, the IEC 60118-13 standard confined its interference measurements to reflect the level of bystander interference from users of cell phones at least 1 m from the hearing aid wearer and did not consider measurements representative of what might occur if a hearing aid wearer was attempting to use a DCT. Because hearing aid

**Table 3 Recommended E and H Field Immunity Levels in ANSI C63.19 Standard for Hearing Aids for < 55 dB IRIL and E and H Field Emission Levels for Cell Phones**

| Category | RF Parameters | | | |
|---|---|---|---|---|
| | Hearing Aid Parameters* | | Telephone Parameters | |
| Near Field | E-Field Immunity (CW dB (V/m)) | H-Field Immunity (CW dB (A/m)) | E-Field Emissions (CW dB (V/m)) | H-Field Emissions (CW dB (A/m)) |
| Category U1 | 30.0–35.0 dB (V/m) | −23.0 – −18.0 dB (A/m) | 46 – 51 dB (V/m) +0.5 × AWF | −4.4 – 0.6 dB (A/m) +0.5 × AWF |
| Category U2 | 35.0–40.0 dB (V/m) | −18.0 – −13.0 dB (A/m) | 41 – 46 dB (V/m) +0.5 × AWF | −9.4 – −4.4 dB (A/m) +0.5 × AWF |
| Category U3 | 40.0–45.0 dB (V/m) | −13.0 – −8.0 dB (A/m) | 36 – 41 dB (V/m) +0.5 × AWF | −14 – −9.4 dB (A/m) +0.5 × AWF |
| Category U4 | > 45.0 dB (V/m) | > −8.0 dB (A/m) | < 36 dB (V/m) +0.5 × AWF | < −14.4 dB (A/m) +0.5 × AWF |
| Category UX | Special | Special | Special | Special |

*Hearing aid must maintain < 55 dB IRIL interference level and < 6 dB gain compression.
Reprinted from the ANSI 2001 C63.19 standard by permission.[20]

wearers need to use mobile phones, it became evident that a measurement reflecting the level of user interference was needed as well. The IEC 60118-13 standard is being modified (circulating in draft form at the time of this writing) to include a near-field measurement to assess user compatibility. Thus, the currently proposed revision of the standard contains measurements that attempt to reflect both bystander and user interference levels, without changing use of a Gigahertz Transversal Electromagnetic Mode (GTEM) cell to make these measurements. Drafters of the IEC standard feel that it is sufficient to verify and express the immunity of hearing aids with a far-field test, based on their opinion that it is possible to establish a correlation between the measured far-field immunity level and the immunity level produced by a hearing aid used with a wireless phone held over it. It appears that the IEC standard will have two limits: 75 V/m for general use with cell phones (at low frequencies) and 10 V/m for immunity to bystander interference, both requiring IRIL levels in the hearing aid of 55 dB SPL or better.

**Table 4 ANSI C63.19 Classification Systems Matching for Telephone Radiation and Hearing Aid Immunity as a Function of Level of Usability**

| Usability | Hearing Aid Immunity Category | Telephone Emission Category |
|---|---|---|
| Usable | U0 | U2 |
| Usable | U2 | U0 |
| Usable | U1 | U1 |
| Normal use | U0 | U3 |
| Normal use | U3 | U0 |
| Normal use | U1 | U2 |
| Normal use | U2 | U1 |
| Excellent | U1 or higher | U3 |
| Excellent | U3 | U1 or higher |
| Excellent | U2 | U2 |

A total score of 3 indicates normal use. Adapted from Victorian,[7] with permission.

The concept of an IRIL, as advocated in work done by the EHIMA group[15] and Joyner et al,[16] is incorporated in the IEC standard.

## IEC 60118-13 VERSUS ANSI C63.19

Potential hardship may arise for manufacturers of hearing aids if they need to conform to both standards in order to sell their products in both the United States and in Europe. Currently, ANSI C63.19 standard references the IEC 60118–13 method in an informative annex. However, material in an informative annex of an ANSI standard generally is not considered to be a part of the standard. For the IEC 60118–13 test method to be recognized as an alternative approach, it would have to be placed in the main body of the ANSI standard or be made into a normative annex.

Critics of the IEC test method have noted that a sine wave input signal and a sinusoidal modulation of an RF signal bear little resemblance to real-world use of hearing aids and DCTs, with speech as the desired signal.[7] Members of the ANSI C63.19 working group feel that use of a GTEM cell, as recommended in the IEC 60118–13 standard, results in a far-field measurement and will not produce a valid representation of near-field emissions from DCTIs. Instead, as suggested by Macfarlane[10] and Caputa et al,[23] the ANSI group feels that a dipole is required for valid near-field measurements. A dipole test method is incorporated in ANSI C63.19 standard.[10] The dipole test method attempts to replicate the telephone antenna and account for the near-field emission to the hearing aid wearer. The E field is strongest at the tips of the antenna (dipole), and the H field is strongest at the midpoint of the dipole.[8] However, Caputa et al[23] state that the E field is attenuated in the ear canal, but the H field is enhanced. This phenomenon has a positive effect in reducing the E field part of the interference signal, but also has a negative outcome due to the H field portion of the interference signal being enhanced. The dipole test method simulates near-field illumination of a hearing aid when a DCT is held over it, while the GTEM test method simulates the far-field, plane-wave radiation experienced by a hearing aid from bystander interference produced by another person using a DCT some distance away.

Members of both standards groups are attempting to harmonize the two standards. Mention is made in the introduction of the latest draft of IEC 60118–13 of using the dipole near-field test method to obtain valuable information during design and development of hearing aids. However, some basic differences between the two standards exist at the time of this writing.

- Repeatability of each method. Contrary to previous reports, recent data[33] indicate that the methods have about the same repeatability.
- Ability of each test method to establish both the E field and H field that a cell phone produces in the near field.
- Ability of each test method to predict the amount and type of interference a hearing aid wearer would experience.
- Currently, the ANSI C63.19 working group is initiating a request to see whether correlating the class or categorization structure outcomes obtained by the ANSI C63.19 dipole and IEC 60118–13 GTEM test methods produce the same result.

As of the latest IEC Working Group 13 standards committee meeting in June, 2002, EHIMA and Hearing Industries Association (HIA) are sponsoring further tests to be performed by Delta Acoustics and by Stephen Berger that will compare the repeatability of the dipole and GTEM methods and their measurement results.

## THE FDA POSITION

In 1996 the Food and Drug Administration (FDA) circulated a letter to hearing aid manufacturers and distributors stating that they had received numerous letters from hearing aid wearers regarding their worries about being able to use their hearing aids in the presence of DCTI. The FDA letter went on to encourage hearing aid manufacturers to implement methods of increasing immunity of hearing aids to electromagnetic interference. The letter also suggested that hearing aid manufacturers test their hearing aids for electromagnetic immunity, although testing was not a premarket requirement at that time. Most feel that the FDA will not intervene as long as the hearing aid industry is perceived to be making progress in testing, improving immunity in hearing aids, and characterizing interference. The FDA believes the near-field dipole method in ANSI C63.19 is the proper approach for characterizing electromagnetic interference.[23] The FDA may eventually adopt the ANSI C63.19 standard because they have declared the GTEM cell unacceptable.[23]

## THE TELEPHONE INDUSTRY POSITION

Most hearing aid manufacturers participating in developing the ANSI C63.19 standard feel that the Cellular Telecommunications and Internet Association (CTIA), the trade association for wireless telephone companies, has been generally uncooperative and unresponsive. The CTIA says that analog cellular telephones continue to be available that do not have the interference problem.[25] Some telephone company engineers agree that the dipole is more appropriate than the GTEM cell for providing a representative RF source to simulate the electromagnetic field emanating from a DCT. This is logical because these same telephone company engineers were members of the ANSI C63.19 working group that standardized the dipole test method.[26]

## THE HEARING AID INDUSTRY POSITION

The HIA (located in the United States but dominated currently by European hearing aid companies) and the EHIMA, the European consortium of hearing aid companies, both say the ANSI C63.19 standard is unacceptable in its present form because it uses the dipole test method and does not conform to the IEC 60118–13 user test method. They feel that the repeatability of dipole measurements is relatively poor and that there is no clear correlation between dipole and GTEM cell measurements. Further, HIA and EHIMA feel that having to do two sets of measurements will cause hardship for hearing aid manufacturers and confusion for professionals in the hearing care field and for hearing aid wearers.[27]

## THE CONSUMER'S POSITION

Self Help for Hard of Hearing People and the AG Bell Association for the Deaf believe that hearing aid companies are working hard on immunity improvements, but cell telephone companies are not doing much. AG Bell has petitioned the FCC to have an interference-free cell phone available. Meanwhile, hearing aid designs have continued to improve due to RF filters incorporated into hearing aid microphones and changes in wiring and layout of internal hearing aid construction. Recent HIA statistics indicate that there are only a few complaints about DCTI[21,28] and have reported that the interference problem is basically solved.

## STATUS OF DIGITAL CELL TELEPHONE DESIGNS TO REDUCE INTERFERENCE

In the view of many in the hearing aid industry, telephone companies caused the problem of DCTI, and, therefore, they should be responsible for alleviating the interference problems with improved telephone designs. Ideally, in the spirit of the Wireless Summit convened in January 1996, all telephone companies would have actively investigated methods for reducing the strength of the interfering fields emanating from their telephones, such as shielding and repositioning antennas. To their credit, many of the telephone companies did contribute significant resources in attempting to correct the problem, funding the work of the EMC Center at the University of Oklahoma and helping to prepare the C63.19 ANSI standard.

Some promising results have appeared from this work. For example, a recent remarkable report stated that some DCTs can be used by hearing aid wearers in T-coil mode without accessories to space the telephone away from the hearing aid.[29] Included are the Motorola Startac 7868 and 7867 phones with service by Verizon and Sprint, respectively, and the Samsung SCH3500 phone with service provided by Sprint. This is a great achievement, because an induction coil in a hearing aid transduces the near-field magnetic portion of the DCT interference signal as well as the desired telephone signal.

The technical difficulty of overcoming the interference problem is significant. At first glance, an obvious way of reducing interference would be to reduce the power radiated by the telephones. However, this would also limit the phones' effectiveness in their intended use. Other methods being considered by phone company engineers include: gradually ramping or slowing down the rise and fall times of the modulating waveform to reduce harmonics generated; attempting to cancel the base-band magnetic leakage radiated from the DCT battery, which is rich in low-frequency interference; improved shielding of the DCT; moving the DCT antenna farther away from the ear and using directional antenas.

## METHODS OF ALLEVIATING INTERFERENCE IN HEARING AIDS

Early on to reduce interference, hearing aid components and wiring were tailored to suppress RF pickup within the hearing aid. A commonly used technique is to provide a filter in sensitive areas of the hearing aid circuitry in which a pulsatile RF signal might be picked up. Specialized miniature components became available specifically for filtering out EMI interference in hearing aids.[30] Figure 10 illustrates such an assembly consisting of a chip ferrite bead and two chip capacitors forming a "Pi" EMI filter. The manufacturer's data sheet states that this network can provide about 35 dB attenuation for an RF signal at 900 MHz. Hearing aid microphone manufacturers have used such filters connected inter-

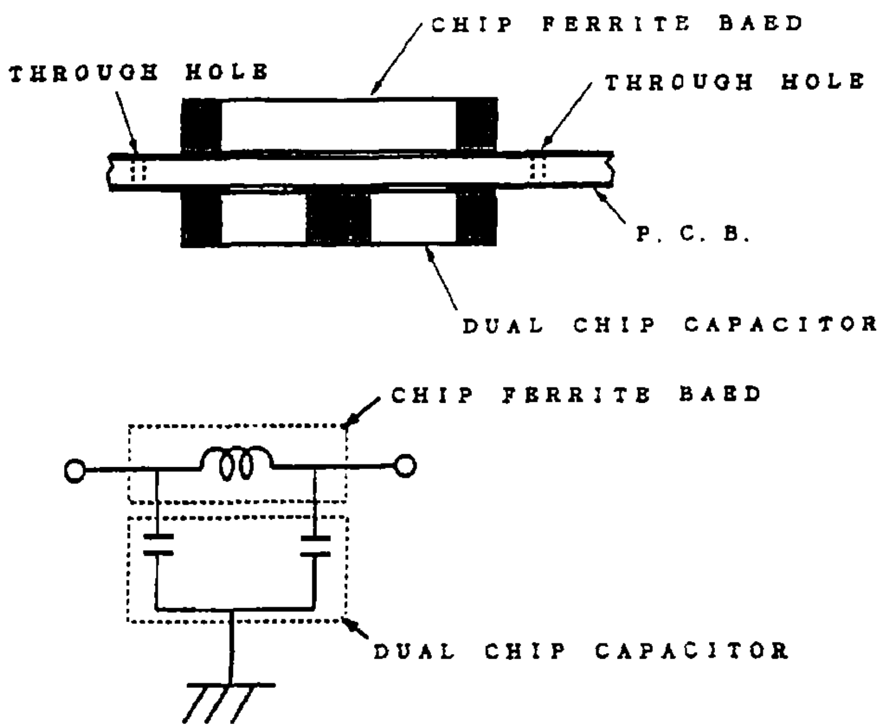


**Figure 10** Subminiature assembly consisting of a chip ferrite bead and two chip capacitors forming a "Pi" EMI filter. Reprinted from Murata (1995)[30] by permission.

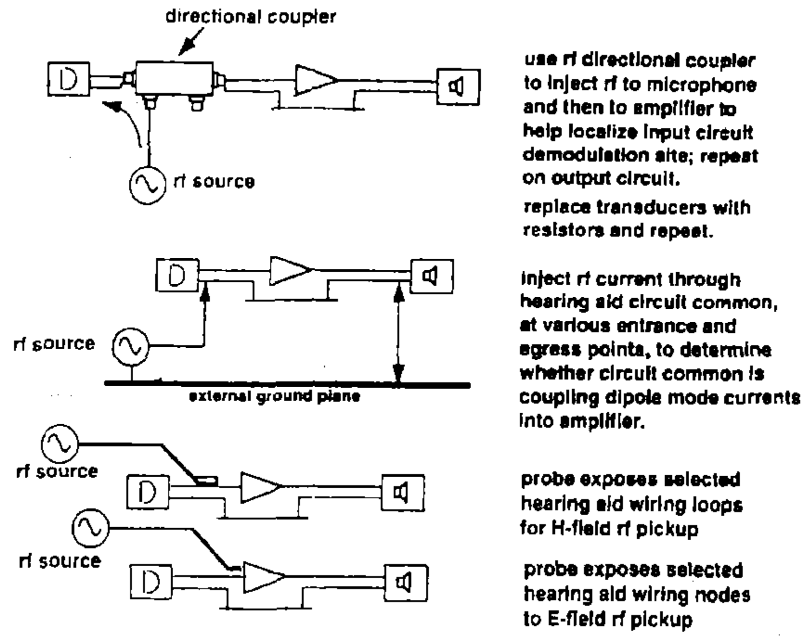


**Figure 11** Test setup to determine susceptibility of a hearing aid faceplate to RF interference. Reprinted from NORTEL (1996)[34] by permission.

nally to the microphone terminals. Hearing aid microphones were introduced with integral RFI filters made with integrated thick film capacitors.[31] Hearing aid amplifiers also have been constructed with such filters connected directly to the electrical terminals of the amplifiers.[32,33] Another common technique for rendering amplifiers less sensitive to external signals is the use of differential signals. With differential signal routing, if the same signal is present on both inputs of an inverting operational amplifier, much of that signal will be canceled by the common mode rejection of the operational amplifier. Many hearing aid manufacturers also have ensured that the wire lengths in their hearing aids are as short as possible, for example, those connecting the microphone to the amplifier, and the wiring is routed in an orientation so as to minimize interference pickup. Other hearing aids were made more immune to interference by applying a conductive metallic coating to the inside surfaces of their plastic housings by sputtering, evaporation, painting, or electro-deposition, or by filling the insides of the plastic case parts with conductive metal.

Even some telephone manufacturers have experimented with hearing aids to see what improvements in immunity to EMI would be possible. For example, Figure 11 shows an experimental setup used by Northern Telecom[34] (NORTEL) to evaluate the susceptibility of hearing aids to injected E and H fields. Figure 12 shows the amount of improvement in E field immunity compared with an untreated faceplate achieved at NORTEL by replacing the microphone with a resistor (of theoretical value only), shortening the receiver wires, and applying foil to the faceplate near the volume control. The graph illustrates the magnitude of injected E field (per IEC 60118–13) required to produce a 55-dB SPL hearing aid output at maximum volume control setting. The investigators reached the following conclusions: the circuit studied was 10 dB more susceptible at 1900 MHz (1.9 GHz) than at 800 MHz; immunity improvements greater than 20 dB could be achieved with shorter receiver leads; greater improvements could be obtained by shielding the leads of components in the hearing aid shell.

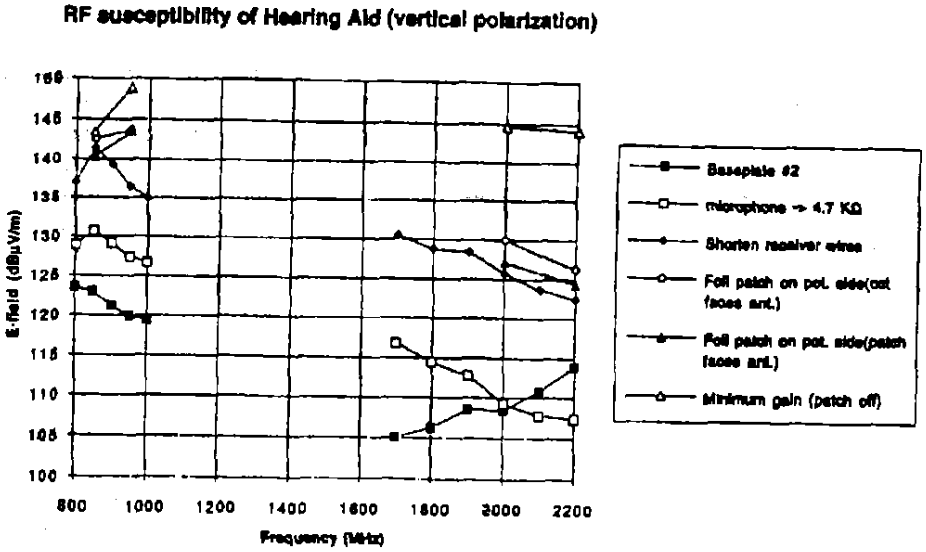


**Figure 12** Reduction in E-field interference susceptibility as a function of frequency produced by several interference treatment techniques. Reprinted from NORTEL (1996)[34] by permission.

Although the telephone industry and hearing aid industry have spent years trying to reduce the DCTI in hearing aids, other methods have been advocated to facilitate use of DCT by persons with hearing loss. Most of these have the disadvantage that they are unnatural or less cosmetically appealing than normal use of the telephone by persons having no hearing loss. However, recently enacted regulations in some states that mandate hands-free cellular telephone operation may make some of these solutions more appealing. The simplest method of hands-free cellular telephone operation requires that a wire connect a listening earpiece to the telephone. Such a system is described in the patent of Boden-Nielsen and Winberg[35] in which the hearing aid wearer wears at least one head-worn hearing aid and a headset that is connected via a relatively long cord (typically 0.5 m) to the DCT. The headset contains a telecoil for one-way transmission of the DCT signals to the hearing aid via induction pickup and a microphone on a boom for communicating back to the DCT. Because the DCT is located remotely on the long cord, interference is substantially reduced. The Hearing Aid Telephone Interconnect System (HATIS) headset system is another means to remove the telephone from close proximity to the hearing aid and to provide hands-free operation. The HATIS system includes a cable having one end that plugs into the headset jack of cellular telephones and the other end plugging into a connector similar to a direct audio input jack in a BTE silhouette hearing aid case. The BTE silhouette contains a coil that couples inductive energy transduced from the DCT output signal into any hearing aid with a telecoil. A boom or in-line microphone allows the hearing aid wearer to speak with the DCT in a remote location.

Another patent describes an electromagnetic interference canceller for an audio amplifier[36] in which the interference signal characteristics are detected and synthesized. A signal generator in the amplifier synthesizes an electrical signal that includes the desired audio signal component and the interference signal. Once known, the interference is removed by a canceller network, leaving the desired acoustic signal. Telephone manufacturers have been investigating solutions such as special battery designs that reduce noise currents produced within the telephone, special antenna designs, and RF shielding within the telephone.[33]

Killion and Matzen[37] proposed that one could fill in the dead spaces in the modulated RF waveforms to reduce interference. Methods to do this included transposing the DCT carrier frequency to a harmless frequency band or designing a hearing aid that senses the RF and shifts a DC bias at a rate and amplitude suitable to counteract the modulation. Another possibility is raising the acoustic output of DCTs to increase the SNR, or the electromagnetic output power of DCTs could be decreased to reduce interference.[13]

## CONCLUSION

Currently, enough progress has been made in hearing aid design improvements to minimize the problem of DCTs causing significant interference in hearing aids. At this time, two different measurement methods can be used to characterize the amount of interference that would be produced. The ANSI C63.19 standard uses a dipole antenna for interference measures and classifies phones and hearing aids into categories according to the degree by which combining a specific phone and hearing aid would be acceptable in use. The IEC 60118-13 standard recommends pass–fail criteria for bystander and wearer interference using a GTEM cell test method. Currently, the members of both standards organizations are studying these two test methods with the intention of harmonizing the outcome for predicting whether a specific cell phone–hearing aid combination will be acceptable or not in use.

ACKNOWLEDGMENTS

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## ABBREVIATIONS

| | |
|---|---|
| AM | amplitude-modulated |
| ANSI | American National Standards Institute |
| BTE | behind the ear hearing aid |
| CDMA | Code Division Multiple Access |
| CIC | completely in the canal hearing aid |
| DCT | digital cellular telephone |
| DCTI | digital cellular telephone interference |
| E field | electric field |
| EHIMA | European Hearing Instrument Manufacturers Association |
| EMC | electromagnetic compatibility |
| EMI | electromagnetic interference |
| FCC | Federal Communications Commission |
| FDA | Food and Drug Administration |
| GSM | Global System for Mobile Communications |
| GTEM | Gigahertz Transversal Electromagnetic Mode |
| H field | magnetic field |
| HATIS | Hearing Aid Telephone Interconnect System |
| IEC | International Electrotechnical Commission |
| IRIL | input referred interference level |
| ITC | in the canal hearing aid |
| ITE | in the ear hearing aid |
| NAL | National Acoustics Laboratory |
| NORTEL | Northern Telecom |
| OIRIL | overall input referred interference level |
| PCS | Personal Communication Systems |
| RF | radio frequency |
| SNR | signal-to-noise ratio |
| SPL | sound pressure level |
| TDMA | Time Division Multiple Access |

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